



Electrodeposition of Nanocrystalline Co-P Coatings as a Hard Chrome Alternative

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Sustainable Surface Engineering for Aerospace & Defense
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Hard Chrome Plating

(Why do we use it?)



■ Why Chrome plating?

Engineering hard chrome (EHC) coatings are used extensively in both industry and military applications due to their excellent performance characteristics.

- Wear
- Corrosion Resistance
- Dimensional Restoration

■ Where is Chrome Plating Used?

- Manufacturing and repair
- Dynamic components
- Hydraulic actuators
- Propeller hubs
- Engines
- Landing Gear





Hard Chrome Plating (The Problem)

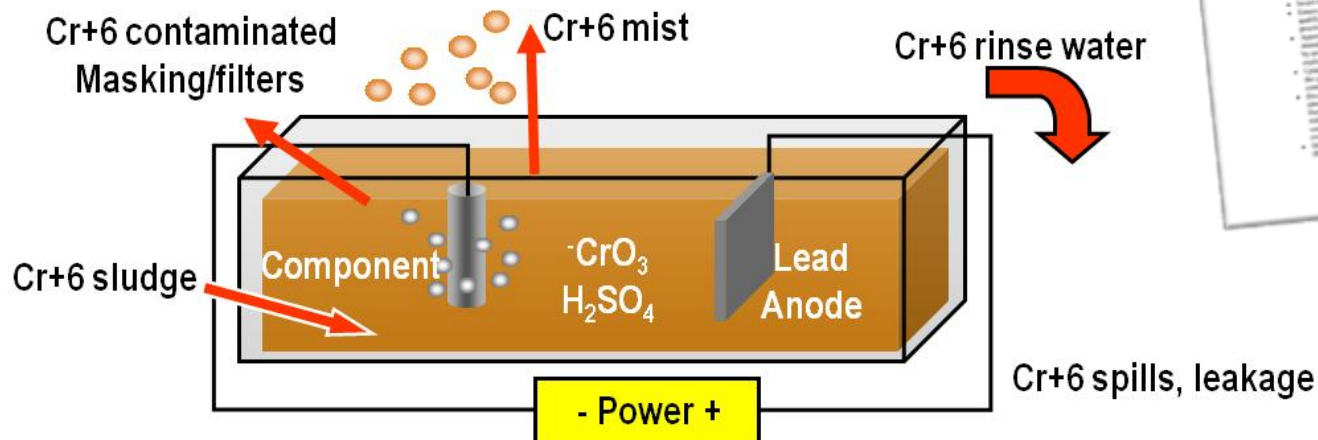


■ Hard Chrome Plating Environmental & Health Hazards

- Hard chrome plating utilizes chromium in the hexavalent state (Cr^{6+})
- Cr^{6+} is a known carcinogen and poses a health risk to operators
- OSHA lowered the Cr^{6+} PEL from $52 \mu\text{g}/\text{m}^3$ to $5 \mu\text{g}/\text{m}^3$

■ 8 Apr 09, Memorandum, DoD Directive

- Hexavalent Chromium Management Policy
- **NAVAIR Cr^{6+} Authorization Process**





Hard Chrome Alternative



Nanovate™

CR



■ Coating applied by electrodeposition

■ Pulsed Current Waveform Engineering

- Frequency (Hz) = $1/(t_{on}+t_{off})$
- Duty Cycle (%) = $t_{on}/(t_{on}+t_{off}) \times 100$



■ Electrodeposited nanocrystalline materials

- Favors nucleation of new grains over growth
- Results in an ultra-fine grain structure
- Uniform throughout thickness

■ Leads to unique properties

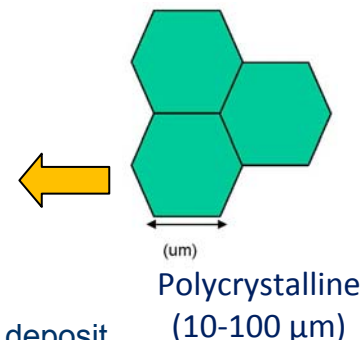
- ↑ Yield Strength, wear, ultimate tensile strength
- ↑ Density
- ↓ Coefficient of friction

(Smaller grain size impedes dislocation movement and increases yield strength)

Hard Chrome Deposit



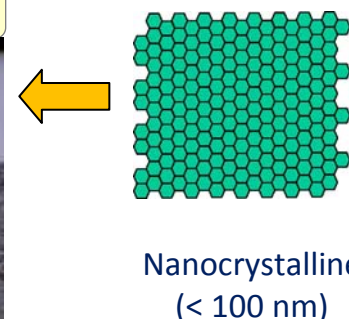
Cross section of typical EHC deposit showing macro cracks. Average grain sizes of 10 – 100 μm .



*Nanovate™ CR



Cross section of Nanovate™ CR deposit. Process creates electrodeposits with grains of 20 nm or less (1000 times smaller).



*Nanocrystalline Co-P Deposit



Hard Chrome Alternative

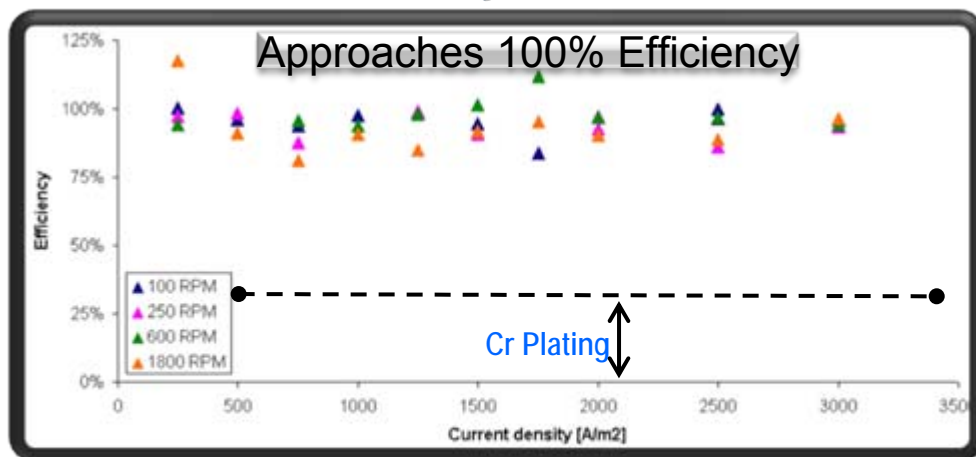


■ Process Comparison

	Nanovate™ CR	EHC
Deposition Method	Electrodeposition (Pulse)	Electrodeposition (DC)
Part Geometries	LOS and NLOS	LOS and NLOS
Efficiency	85-95%	15-35%
Deposition Rate	0.002"-0.008" /hr	0.0005"-0.001" /hr
Emission Analysis	*Below OSHA limits	Cr+6



■ Cathode Efficiency



Nanovate™ CR Plating Tank at FRCSE

- Up to 8X faster than Chrome plating
- Increased throughput
- One Nanovate CR tank can replace several EHC tanks
- More efficient (~ 90% Reduced power consumption)
- Bath is Stable

*Co PEL is 20 µg/m³



Technology Development



- Developed and demonstrated at the lab scale
- Scaled up to industrial production & moved to DoD depot
- US Patents 5,433,797, 5,352,266, 7,320,832, 7,553,553

ESTCP WP-0936

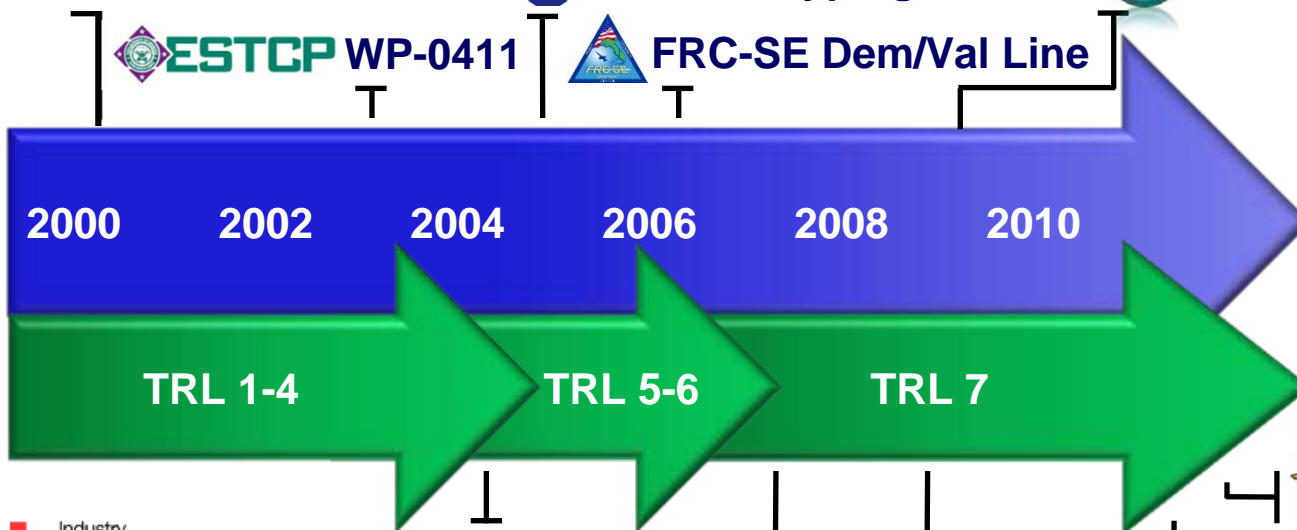
NESDI 348

ITI Prototyping Line

FRC-SE Dem/Val Line

SERDP PP-1152

ESTCP WP-0411



Industry Canada
Industrial Technologies Office
TPC 710 - 492064

Enduro Industries
Pilot Line



2008-A-1455

P&WC
Dem/val
Line

SADI
780-505205



Technology Dem/Val Site (Full Operating Capability)



CIP # 0466

■ NAVAIR Fleet Readiness Center Jacksonville

- Dem/Val line in operation since 2006
- 250 gallon Plating Tank
- Pulse Power supply (1500A Peak Current)
- Activation tank used for most all alloys



Dem/Val Plating Tank



Power Supply



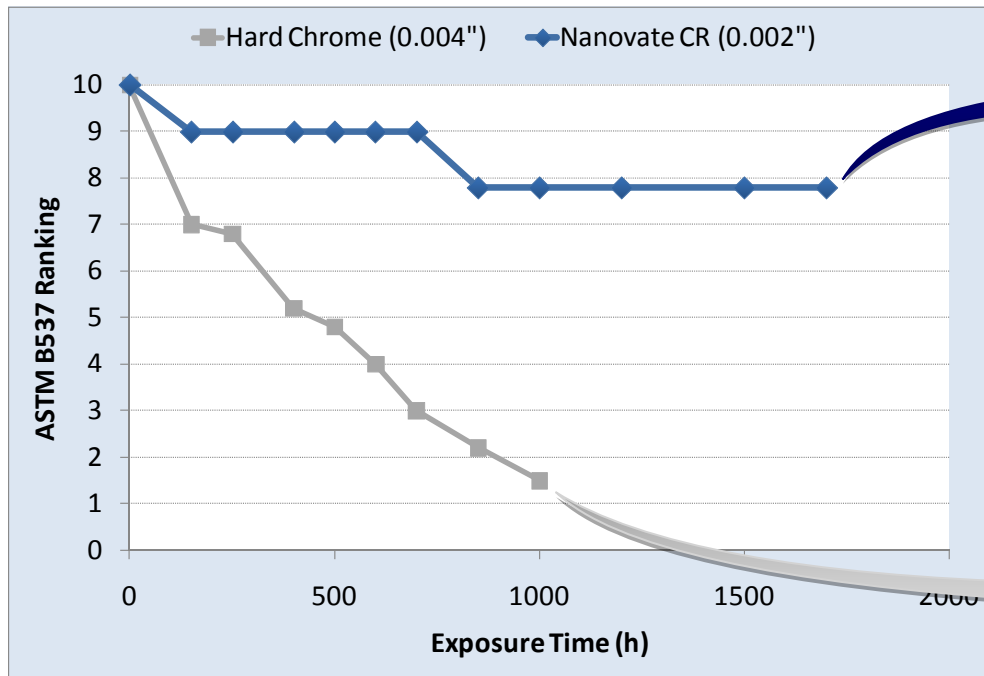
Remote Controller



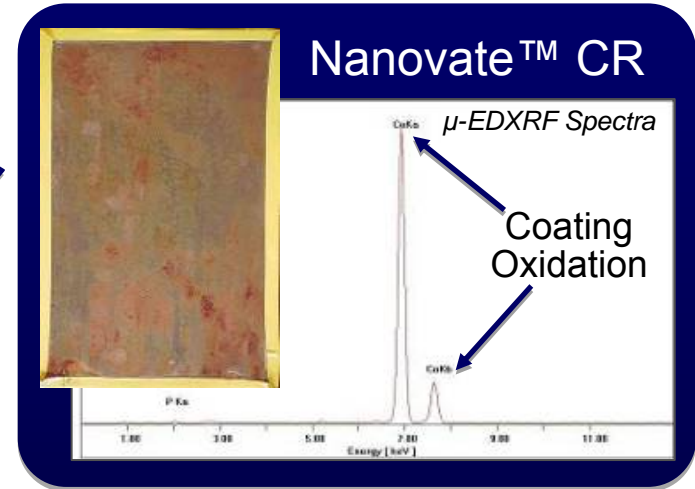
Acid/Fluoride Activation tank



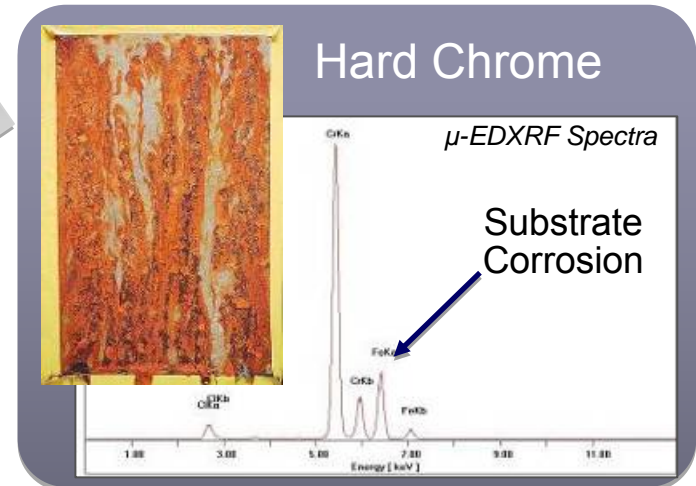
Corrosion Properties



**ASTM B537 Ranking following
ASTM B117 Salt Spray**

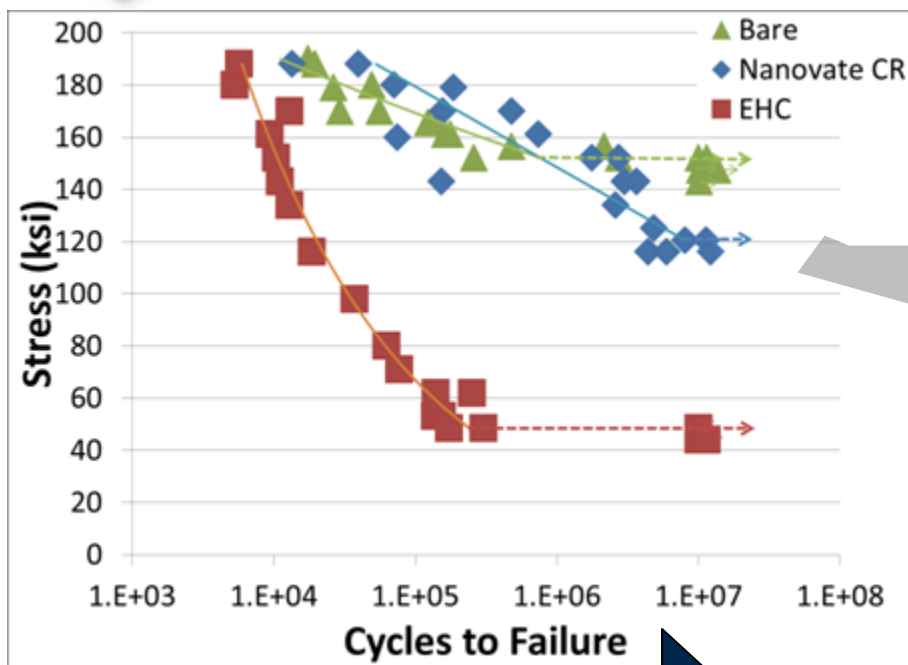


* Photos shown following 165 hrs



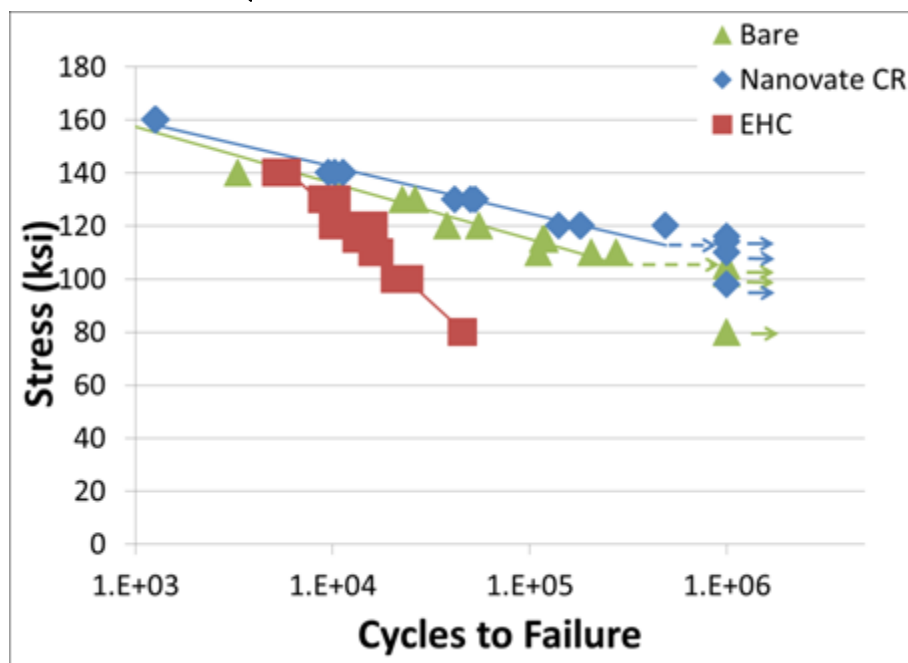


Fatigue Properties



Rotating Beam Fatigue
4340 substrate (UTS: 260-280 ksi)
Significant credit vs. EHC
Comparable to bare

Axial Fatigue (R=-1)
4340 substrate (UTS: 180-200 ksi)
Significant credit vs. EHC
Credit vs bare

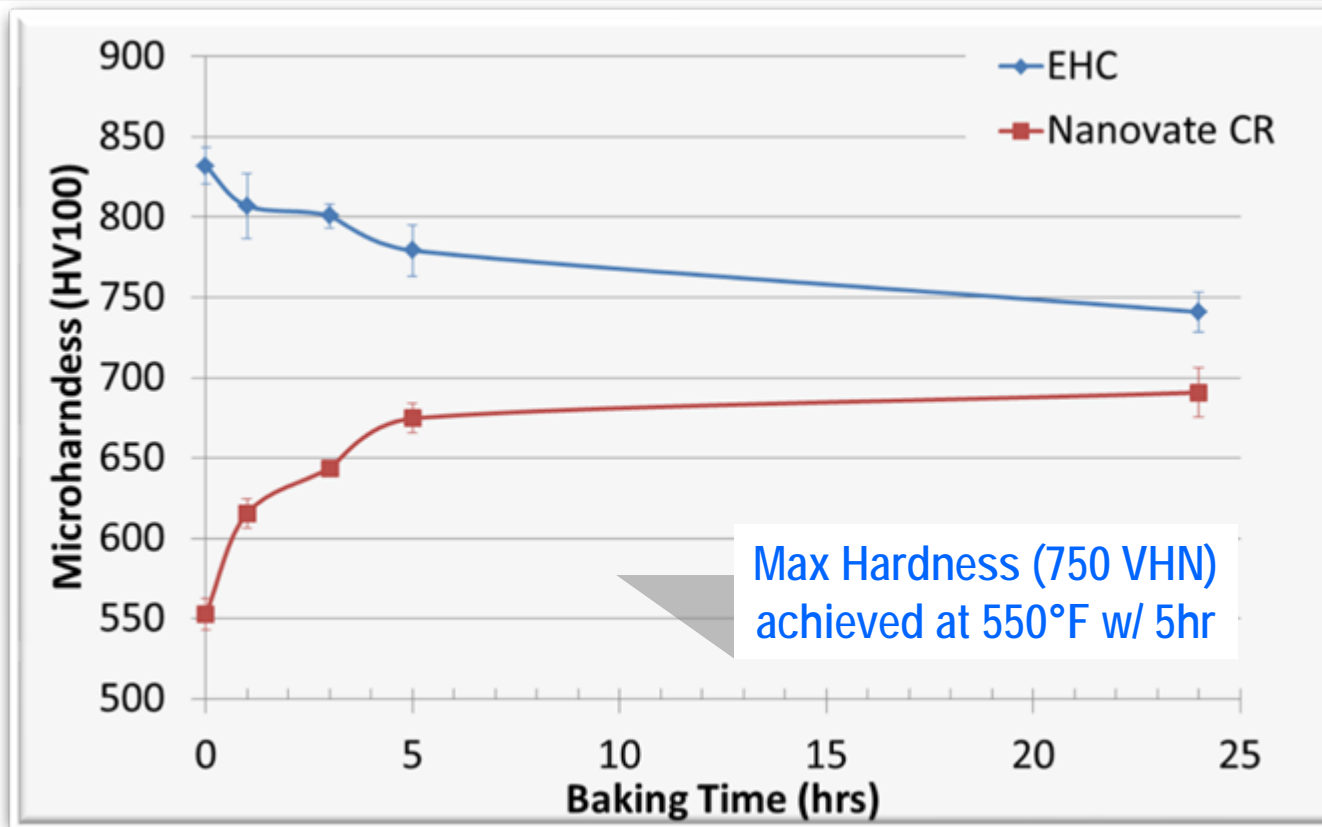




Hardness Properties



Nanovate CR hardness comparable to EHC after annealing at standard conditions for hydrogen embrittlement bakeout (375°F)





Technical Progress (Masking Evaluation)



- Maskants evaluated and downselected
 - Enthone: Enplate Stop Off No. 1
 - Tolber: Microshield
- No adverse effects on bath or deposit quality
- Demonstrated on T45 pivot component



T-45 pivot shown with Enthone Maskant



Technical Progress (Coating Removal Evaluation)



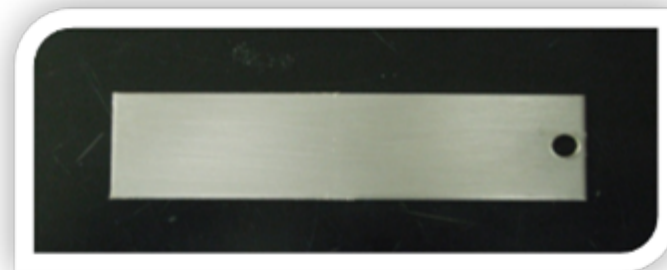
- **Strippants evaluated and downselected**
 - (3) nitro-organic oxidizers with amino compounds
- **0.001"-0.004"/hr removal rates**
- **MacDermid METEX SCB Electroless Nickel Stripper was tested at JAX successfully.**



Pre-plate coupon



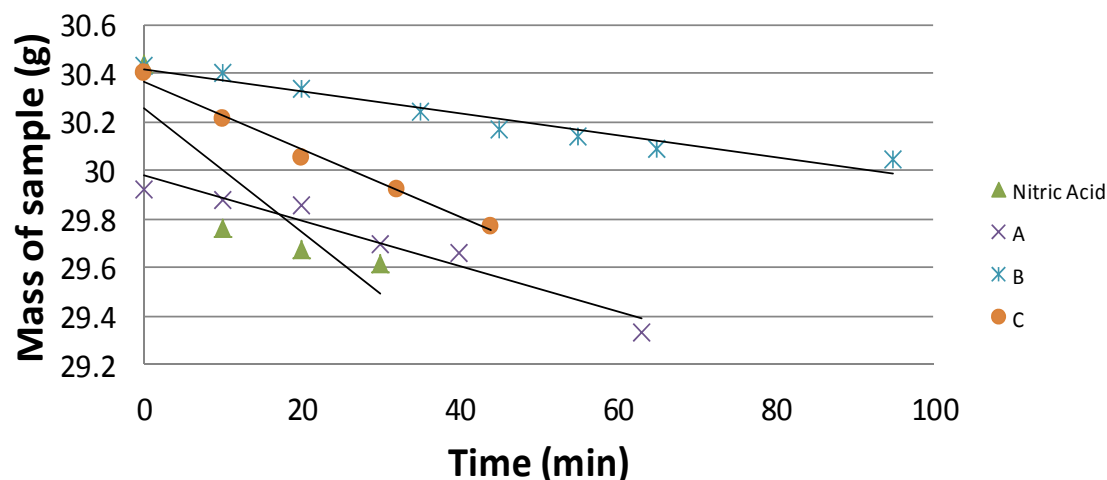
Plated coupon



Stripped coupon

Mass removal over time

(slope of linear fit used as performance metric of stripping rate)





Technology Dem/Val at JAX (JTP Progress)



WP-0936 – Feb 2011



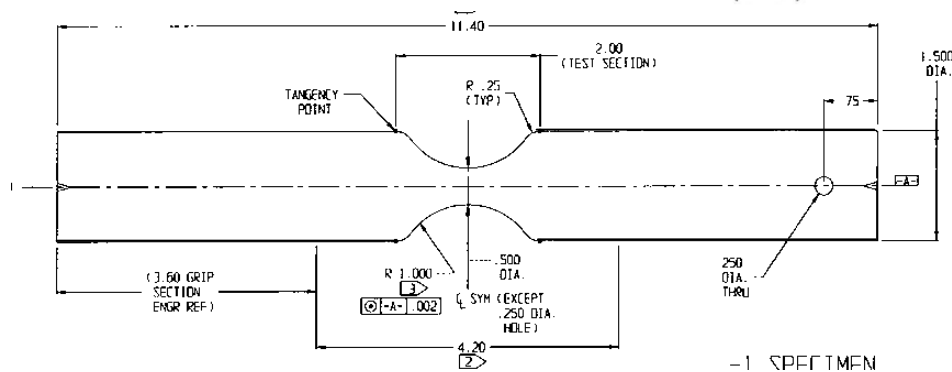
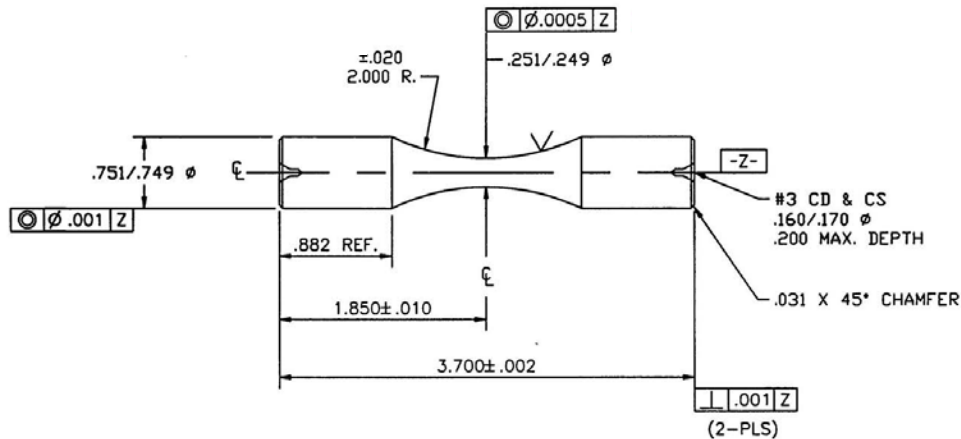
ESTCP JTP & Dem/Plan

24 Core Tests Defined in JTP

- Coating Quality
 - Appearance, Thickness, Porosity, Hardness, Grain size
- Ductility
- Stress (internal)
- Fatigue (Axial)
- Corrosion (B117, SO₂, Beach. OCP)
- Adhesion
- HE, HRE
- Fluid Compatibility
- Wear
 - (Taber, PoD, Rig, Falex, Gravelometry, SATEC)

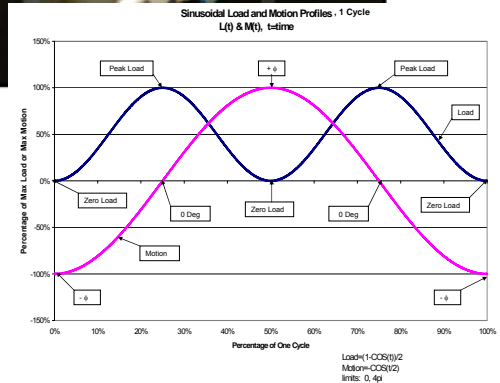
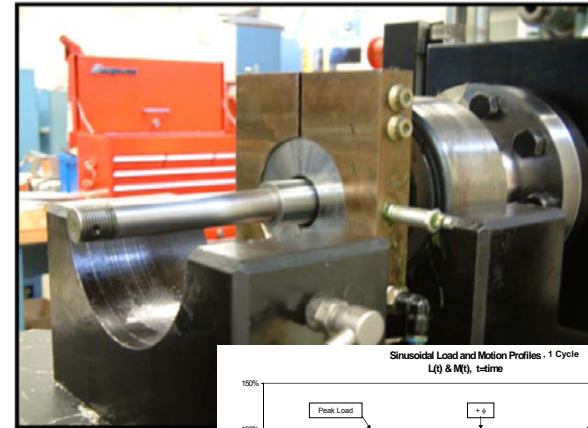


Fatigue/Wear Testing



Axial Fatigue Test

- 4340 steel (260-280 ksi)
- Shot peened
- R ratio: $R = -1$

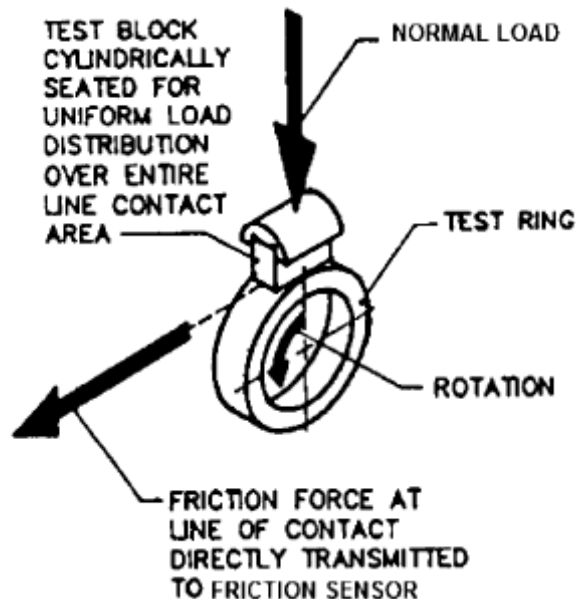


SATEC Oscillating Load Test

- Boeing Specific Test
- Pin/Bushing Oscillating Wear Test
- Constant/ Sinusoidal load-motion profile

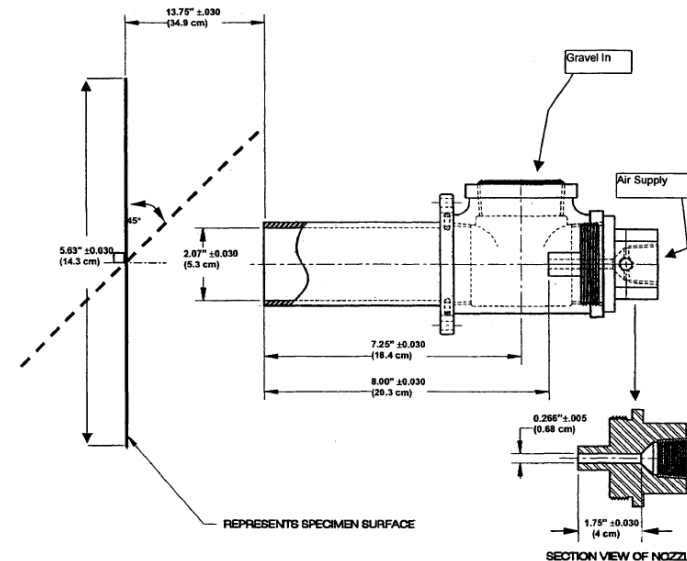


Wear Testing



FALEX Block on Ring

- Test per ASTM G77
- determines the resistance of materials to sliding wear
- Different Alloy/Coatings against Ring



Gravelometry

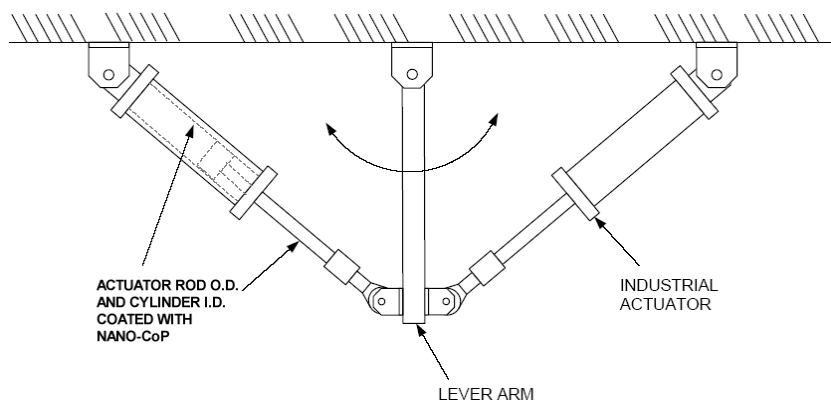
- Test per ASTM D3170
- Specimens mounted perpendicular to projected path
- Pea size gravel; air pressure 70 psi



Endurance Rig Testing



- Assess wear performance vs. chrome as an ID actuator
- Test developed by Messier-Dowty
 - 20,000 Cycles
 - Observe the effect of surface finish, seal types, and hardening condition



Endurance Test Rig Schematic

Test Matrix*

Coating	Surface Finish (Microinches)	Piston Seal	Rod Seal
EHC	12-16	Buna-N Tee Seal Nitrile Butadiene Rubber	Buna-N Tee Seal Nitrile Butadiene Rubber
EHC	4-6		
nCoP	12-16		
nCoP	4-6		
nCoP	12-16		
HEBake	4-6		
nCoP	12-16	Viton Tee Seal Synthetic Rubber Fluoropolymer Elastomer	Viton Tee Seal Synthetic Rubber Fluoropolymer Elastomer
HEBake	4-6		
nCoP	12-16		
Hardenin g Heat Treat	4-6	PTFE Cap	Spring Energized PTFE
nCoP	12-16		
EHC	12-16	Buna-NO- Ring/ Back-up- Nitrile Butadiene Rubber O-Ring	Buna-NO- Ring/ Back-up- Nitrile Butadiene Rubber O-Ring
nCoP	12-16		

**In kind funding (Messier-Dowty)*

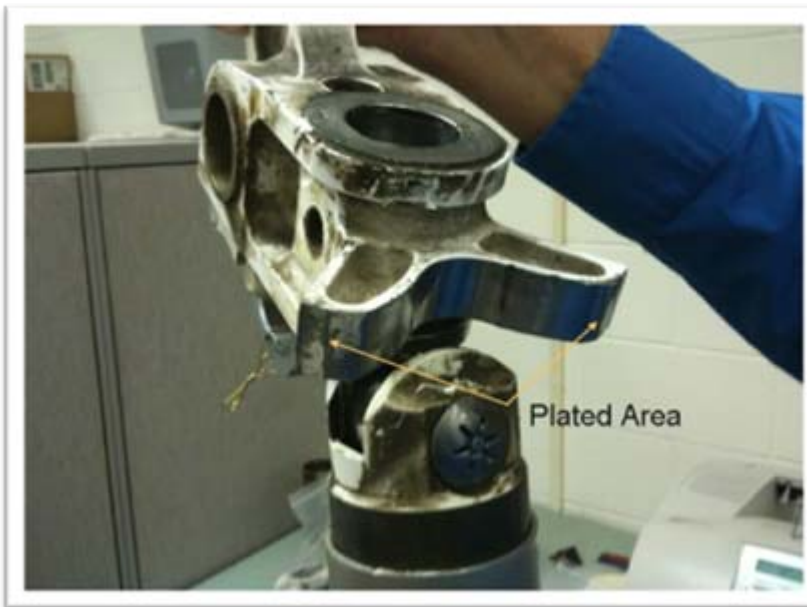


Dem/Val Components T-45 Pivot Assembly



NAVAIR JAX Dem/Val for Air Vehicle Components

■ T-45 Arresting Hook Pivot Assembly



Pivot Assembly



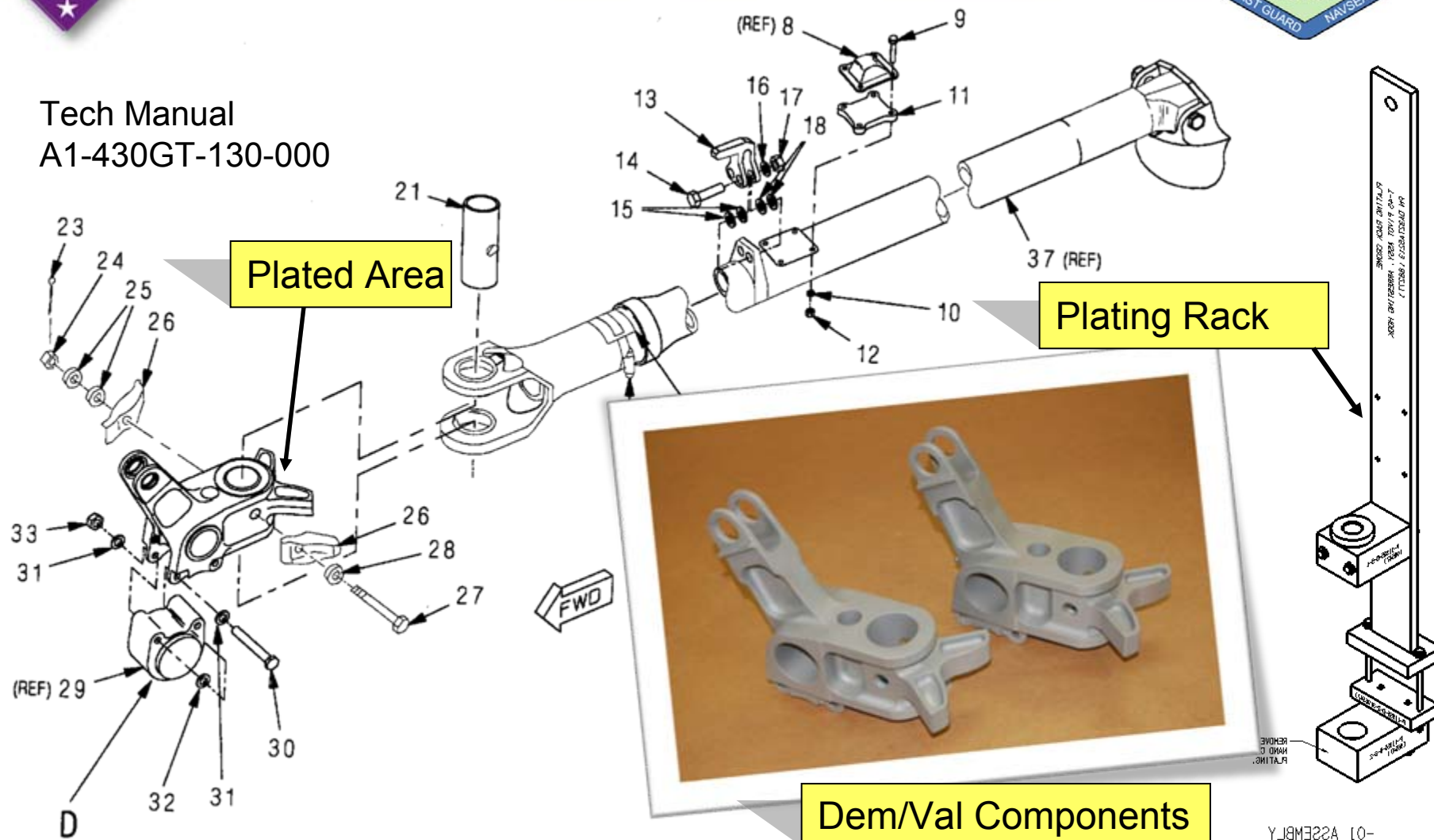
T-45 Goshawk Trainer Aircraft



Dem/Val Components T-45 Pivot Assembly



Tech Manual
A1-430GT-130-000





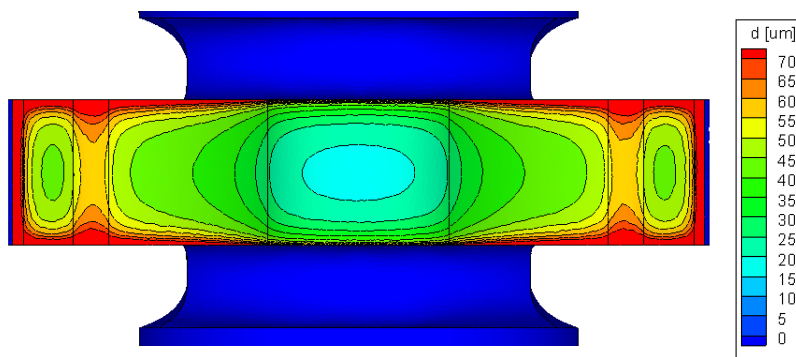
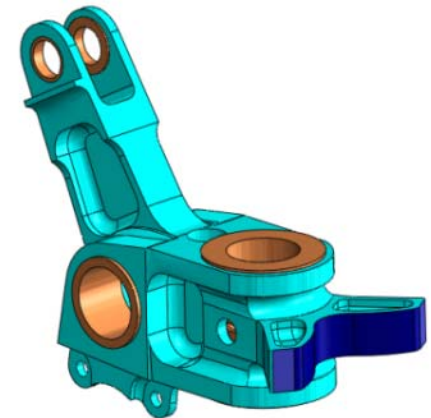
Electroplating Simulation: T-45 Pivot Assembly



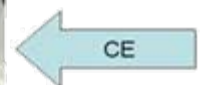
Electrochemical Modeling



- Conducted chemical characterization for model input
- Optimize current density distribution
- Control composition of electroplate
- Optimize coating properties
- Applied simulation to a complex geometry – T45 Pivot Assembly



T-45 Pivot Assy



Bath Characterization



Potential Dem/Val Component Lifting Arm Pin



NAVAIR Lakehurst – Lifting Arm Pin

- Spotting Dolly- Lifting Arm Axel Pin
- EHC vs. Nanovate Cr vs. E-Ni



Various Lifting Pin Systems



Spotting Dolly Lifting Arm



NAVSEA Leveraged Effort LVS Hydraulic Cylinder



NAVSEA (NESDI & OSD Leveraged Effort)



■ Marine Corps MK48 LVS (Logistic Vehicle System) Hydraulic Cylinders

- (1) Evaluate coatings on steel and carburized steel laboratory panels
- (2) Evaluate optimum coatings with accelerated corrosion testing (GM9540P)
- (3) Field test on MK48 vehicles

Goals:

- Develop selection criteria for implementation into system repair / rebuild and spare parts sourcing
- Reduce corrosion maintenance requirements and repair costs of vehicles





NAVSEA Leveraged Effort LVS Hydraulic Cylinder



- Phase I: (*Carburized 1018 Steel Coupons)
 - Unofficial test results
 - ASTM B117 (passed)
 - ASTM F1978 Taber Abrasion (passed)
 - ASTM B571 Impact, Chisel/Knife, Peel (passed)



Taber abrasion



Impact/Adhesion



Corrosion



Corrosion

Rig Test



Nanovate™ CR (center)



Cr
nCoP
X
Y



0 Hrs



480 Hrs



Component Producibility

NAVSEA Refueling Parts



NAVSEA – NESDI Leveraged Effort



■ Refueling At Sea Components (Norfolk Naval Shipyard)



4340 Steel Bearing Housings



17-4 PH Stainless Roller Shafts



Component Producibility

Boeing Aircraft Parts



Boeing Seattle – Aircraft Components



■ Boeing Producibility Items



737 Trunnion Pin – 4340M



787 Drive Shaft – 4340M



Component Producibility

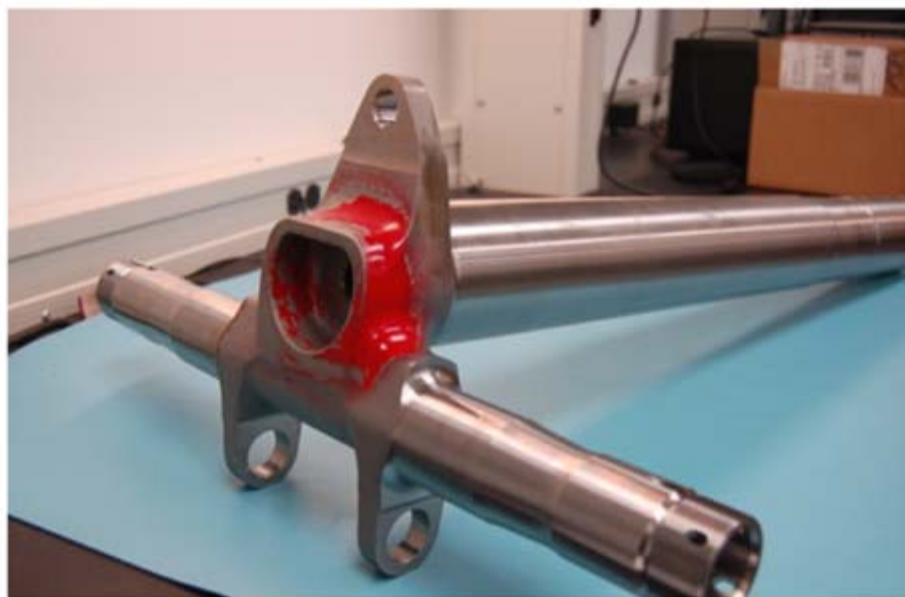
Landing Gear



Messier Dowty – V-22 Components



■ Messier-Dowty Producibility Items



V-22 NLG Piston



V-22 Osprey



Commercial Uses Prototyping & Development



■ Integran Technologies, Inc. (Toronto Canada)



- Nanovate CR prototyping line in operation since 2004
- 600 gallon Plating Tank
- In-line activation tanks
 - Mild steel, alloy steels, stainless steels, aluminum, Inconel, nickel...
- JTP sample production
- Commercial prototyping
 - Hydraulics, valves, pistons, shocks, engines, actuators, landing gear...
 - OEM and R&O



600 gal Plating tank at Integran (2010)

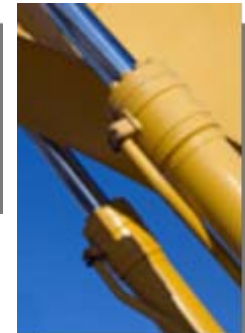


Commercial Uses Enduro Industries, Inc.



■ Enduro Industries, Inc. (Hannibal, MO)

- Nanovate CR process line installed and in operation since 2008
- Applying Nanovate CR to mild and induction hardened steel bars for use in hydraulic actuators for fluid power
- 700 gallon Plating Tank
- Integrant provides on-going support of line
- Milestone: 1,000,000 Amp-hrs of production plating





Commercial Uses P&WC

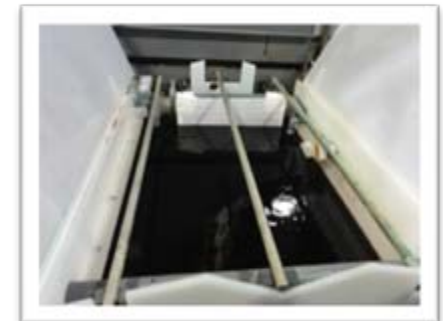
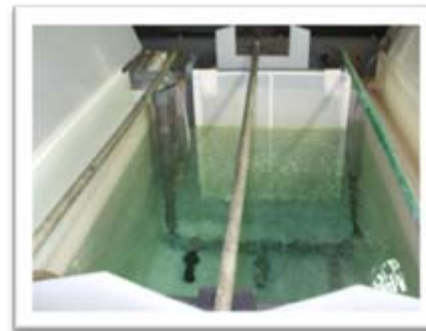


■ Pratt & Whitney Canada (Longueil, Canada)

- EHC replacement for R&O of engine components
- Retrofit equipment to convert to Nanovate™ CR Dem/Val Process Line
- Process line in use since Nov 2010
- 250 gallon Plating Tank



Support provided by:



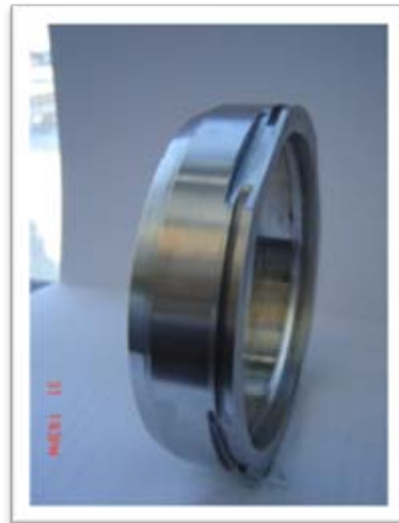


Commercial Uses P&WC



- Demonstration components plated for PT6 platform (shown after machining):

- Prop shaft
- Seal runner



Seal runner
plated at PWC (Jan 11)



Prop shaft plated at ITI (Oct 10)



Prop shaft plated at PWC (Jan 11)



Turbo Prop PT6



Summary



■ Nanovate CR (nCo-P):

- Environmentally compliant EHC alternative
- Process compatible with existing plating infrastructure
- Reduced energy consumption, increased throughput
- Production process in commercial use (TRL 7)

■ Nanovate CR Material Properties

- Enhanced corrosion and wear
- Non-embrittling
- Improved fatigue performance vs. EHC

■ Future work (WP-0936)

- Performance testing (JTP)
- Dem/Val at NAVAIR JAX Depot
- OEM Producibility Components

For more information...



Visit our
booth at
ASETS
Defense



Questions



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IH Assessment at NAVAIR JAX



- NAVAIR-JAX IH assessment on Co emission on the Dem/Val tank.



DATE:	PERSONAL SAMPLING RESULTS (8-HR TWAS)	AREA SAMPLING RESULTS (8-HR TWAS)	VENTILATION MEASUREMENTS (TAKEN ON THE PULL SIDE)	DRY BULB READINGS (2)	RELATIVE HUMIDITY (3)
8 Aug 2007	Below the LOD	0.0023 mg/m ³	3519 FPM	Initial: 79.1°F Final: 97.3°F	Initial: 100% Final: 58%
9 Aug 2007	Below the LOD	0.0074 mg/m ³	3545 FPM	Initial: 81.2°F Final: 97.6°F	Initial: 100% Final: 58%
16 Aug 2007	Below the LOD	0.0017 mg/m ³	4001 FPM	Initial: 79.0°F Final: 94.4°F	Initial: 91% Final: 51%
22 Aug 2007	Below the LOD	Below the LOD	4366 FPM	Initial: 78.5°F Final: 95.0°F	Initial: 94% Final: 50%
24 Aug 2007	Below the LOD	Below the LOD	4088 FPM	Initial: 77.5°F Final: 94.2°F	Initial: 100% Final: 58%

Co PEL is 20 µg/m³



Dem/Val Component Spread Cylinder Hydraulic Rod



NAVAIR Lakehurst – Ground Support Equipment



- Spread Cylinder Hydraulic Rod (A/S32A-32 Aircraft Towing Tractor “Spotting Dolly”)
- Supply System Risk



Spread Cylinder Rod in Assembly



Actuator Assembly

Two Different Sizes Shown



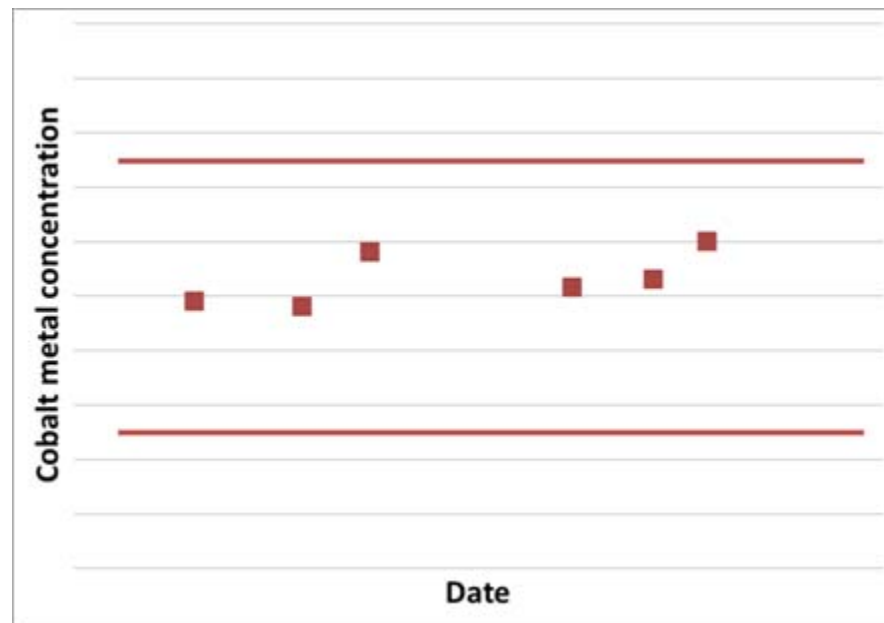
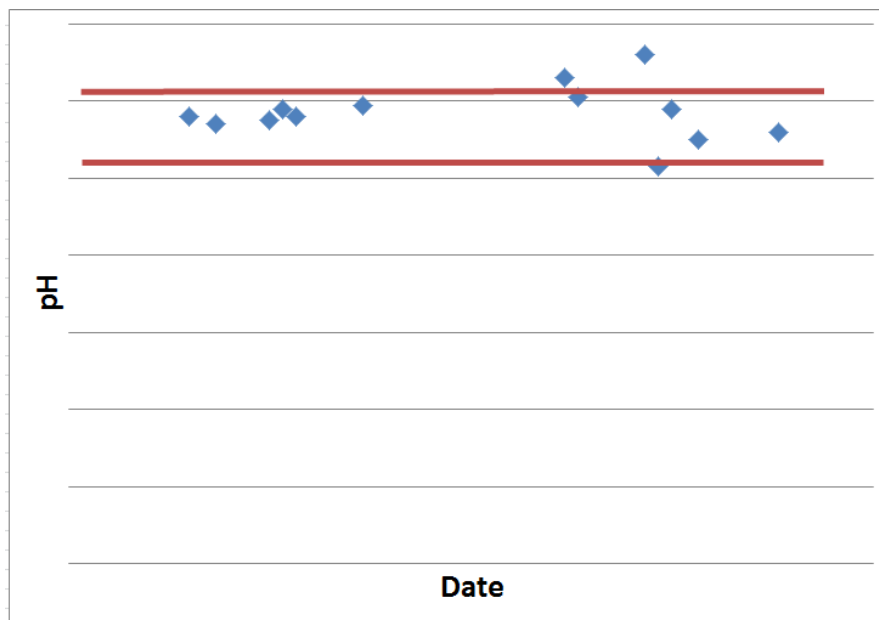
Coating Properties



		Nanovate CR	EHC
Appearance		Pit, Pore, Crack -free	Microcracked
Ductility		2-7%	<1%
Hardness	<i>As-Deposited</i>	530-600 VHN	Min. 600 VHN
	<i>Heat Treated</i>	750 VHN	-
Adhesive Wear (Pin-on-disk)	<i>Wear loss</i>	$6-7 \times 10^{-6} \text{ mm}^3/\text{Nm}$	$9-11 \times 10^{-6} \text{ mm}^3/\text{Nm}$
	<i>Coefficient of friction</i>	0.4-0.5	0.7
	<i>Pin Wear</i>	Mild	Severe
Corrosion <small>†ASTM B537 Rating</small>	<i>Salt Spray ASTM B117</i>	† Protection Rating 8 (1000 h) @ 0.002"	† Protection Rating 2 (1000 h) @ 0.004"
Hydrogen Embrittlement	<i>ASTM F519</i>	Pass with bake	Pass with bake
Fatigue	<i>Axial & Rotating Beam</i>	Credit vs. EHC Comparable to bare	Significant debit vs. bare



Commercial Uses P&WC



- Technology transfer underway
- Integran provides on-going support for the line
- Early process monitoring demonstrates good production control

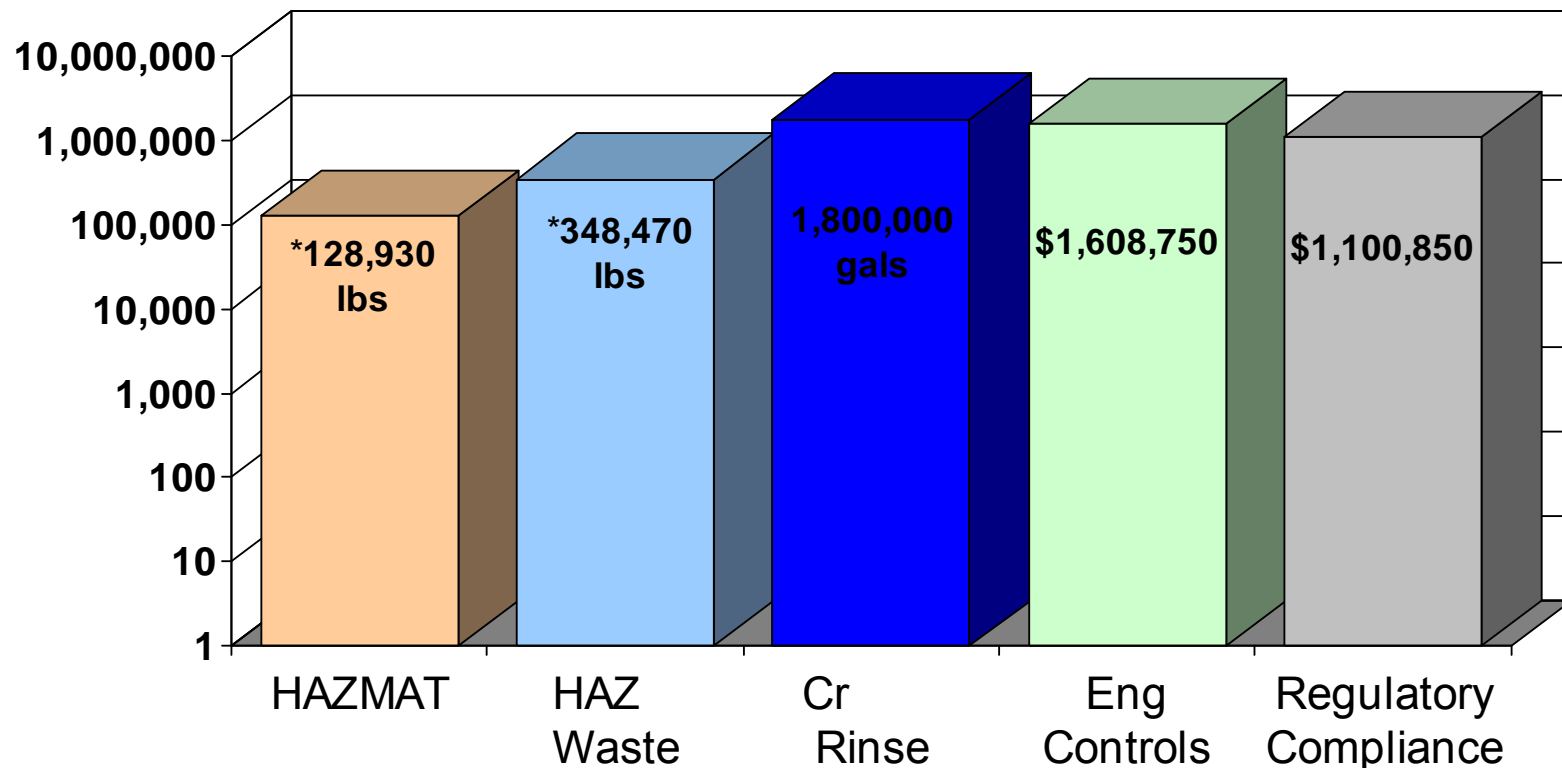


Environmental Driver/Benefit



(Hexavalent Chromium Plating at Navy FRCs)

■ Estimated NAVAIR P2 Savings over 10 Yrs



Note: the above projected savings are assumptions based on FRC-SE data extrapolated to other Navy FRCs

* Estimated amounts due to chrome plating based on average Environmental Systems Allocation (ESA) data extrapolated across all FRCs over a 10 yr period



Cobalt Environment & Worker Safety



Cobalt Air Emissions – US EPA (Environmental Protection Agency)

- Emission limit different by state
 - Typical emission limit without requiring a license is 0.1 tons per year
- EPA estimating tool employed to determine emissions
 - Variables for estimator – bath amps, bath operating hours
 - Typical results are less than 50 lbs (20kg) per year
 - Drivers size of parts being plated, number / shifts (amp hours)
- Nanovate CR emissions below limits

Aqueous System - Environmental

- Dust or fume not produced by the plating process
- Nano materials do not become airborne
 - Nano material plated directly onto the substrate material
 - No sprays to disperse nano materials in the atmosphere

Cobalt Development Institute – Additional Information

- www.thecdi.com/cdi/images/documents/facts/Cobalt_Facts-HS&E.pdf

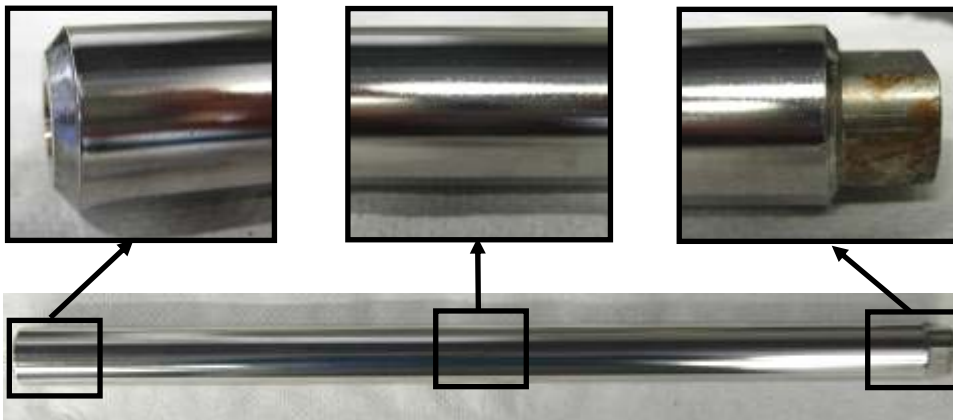
Highly Efficient Process Produces very little Cobalt emissions



Rod-Seal Wear Testing



- Four PH 13-8Mo hydraulic actuator rods
 - Plated with 0.006-0.008" Nanovate CR
 - Hydrogen baked (375°F, 23h) or heat treated (300°C, 6 h)
 - Ground to 6-9 μ inch, 12-16 μ inch or superfinished to $R_a < 4$ μ inch
- Testing conducted at NAVAIR-PAX
 - similar to ID cylinder wear - wear against seals
 - Tests showed Nanovate CR comparable to EHC



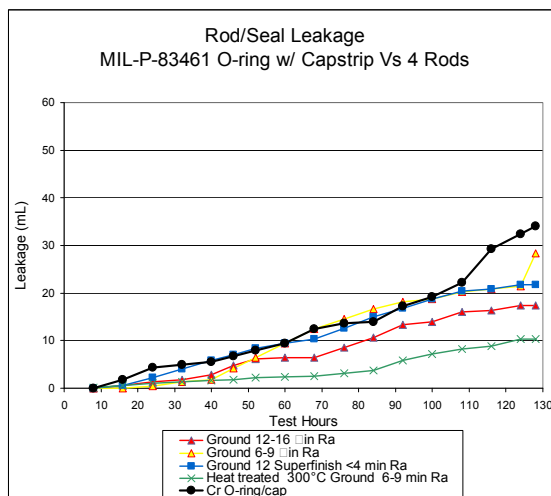
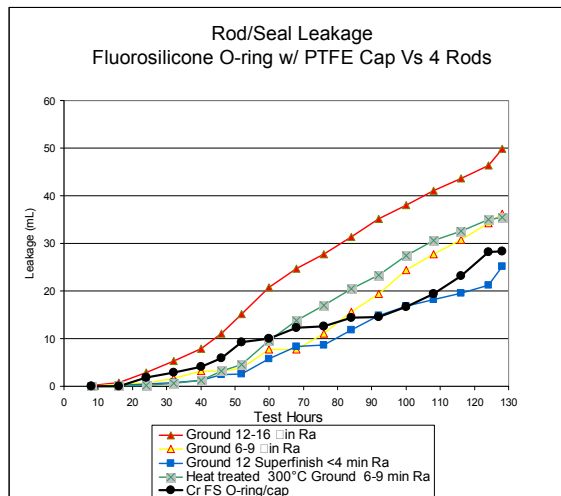
Nanovate CR coated hydraulic rod



Rod-seal test apparatus

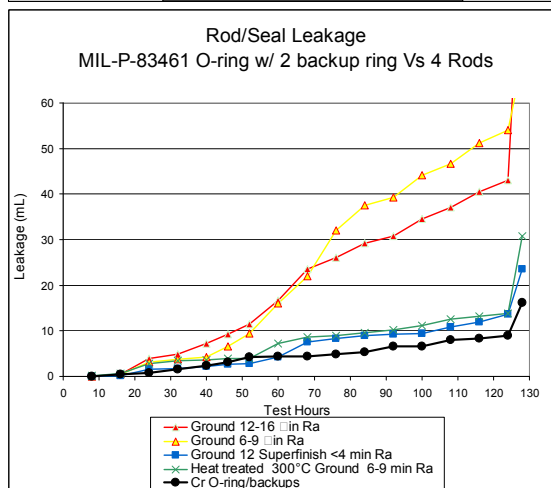
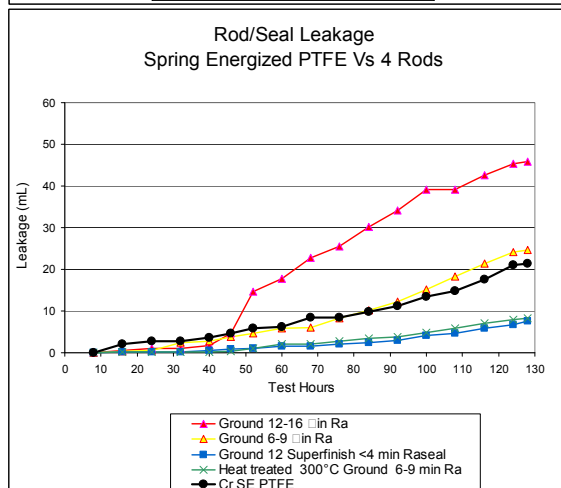


Rod-Seal Wear (Leakage, Various O-rings)



Black lines hard chrome from prior HCAT work

- Different test run
- Nanovate CR roughly comparable with hard chrome
- Ground surfaces higher leakage





Joint Test Protocol



	Sample Production Progress	Sample Completion	Test Completion
Material Characterization	50%	Feb 2011	Mar 2011
Adhesion	0%	Feb 2011	
Fluid Immersion	100%	Feb 2011	
Corrosion	50%		Apr 2011
Adhesive Wear (PoD, BoR)	50%		
Abrasive Wear	0%		Mar 2011
Seal Wear	0%		
Gravelometry	0%		
Bushing Wear	0%		
Fatigue	0%		
Embrittlement	0%		

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